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Abstract

The CASTRIP facility at Nucor Steel's Crawfordsville, Indiana plant is the world's first commercial installation for production of Ultra-Thin Cast Strip (UCS), via twin-roll strip casting. The facility has been producing plain, low-carbon sheet steel since 2002, with a range of structural grades available. The paper outlines some of the main parameters that influence the final microstructure and resultant mechanical properties of plain, low carbon UCS steels that have been recently made by the CASTRIP process, and then describes new Nb microalloyed UCS products that have been made in the CASTRIP process, significantly expanding the range of thin high strength hot rolled strip products for structural applications. In hot rolled UCS steels, niobium was in solute form retarding austenite grain refinement during in-line hot rolling thereby enhancing hardenability and promoting microstructural hardening. In particular, the formation of bainitic/ acicular ferrite microstructures was provided over proeutectoid ferrite in these steels using the CASTRIP process. This enabled higher strength levels to be achieved than with USC plain low carbon steels. Age hardened Nb UCS steels were found to be producible using heat treatment furnaces of a conventional hot dip galvanising line achieving improved strength, while also improving ductility. Yield strength levels for the age hardened and galvanised Nb UCS steels achieved over 550 MPa in combination with good ductility.

Keywords

cast, process, ultra-thin, castrip®, microalloyed, niobium, carbon, plain, development, produced, products, strip

Disciplines

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DEVELOPMENT OF PLAIN CARBON AND NIOBIUM MICROALLOYED ULTRA-THIN CAST STRIP PRODUCTS PRODUCED BY THE CASTRIP® PROCESS.

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ABSTRACT

The CASTRIP®* facility at Nucor Steel's Crawfordsville, Indiana plant is the world's first commercial installation for production of Ultra-Thin Cast Strip (UCS), via twin-roll strip casting. The facility has been producing plain, low-carbon sheet steel since 2002, with a range of structural grades available. The paper outlines some of the main parameters that influence the final microstructure and resultant mechanical properties of plain, low carbon UCS steels that have been recently made by the CASTRIP process, and then describes new Nb microalloyed UCS products that have been made in the CASTRIP process, significantly expanding the range of thin high strength hot rolled strip products for structural applications. In hot rolled UCS steels, niobium was in solute form retarding austenite grain refinement during in-line hot rolling thereby enhancing hardenability and promoting microstructural hardening. In particular, the formation of bainitic/acicular ferrite microstructures was provided over proeutectoid ferrite in these steels using the CASTRIP process. This enabled higher strength levels to be achieved than with USC plain low carbon steels. Age hardened Nb UCS steels were found to be producible using heat treatment furnaces of a conventional hot dip galvanising line achieving improved strength, while also improving ductility. Yield strength levels for the age hardened and galvanised Nb UCS steels achieved over 550 MPa in combination with good ductility.

*CASTRIP® is a registered trademark of Castrip LLC.

KEYWORDS: Direct Strip Casting, UCS, Ultra-Thin Cast Strip, Acicular Ferrite, Mechanical Properties, Formability, Niobium, Microalloying.

INTRODUCTION

The CASTRIP facility at Nucor Steel's Crawfordsville, Indiana plant is the world's first commercial installation for the production of Ultra-Thin Cast Strip (UCS), via twin-roll strip casting. The facility has been producing plain, low-carbon sheet steel since its start-up in 2002. Strip thicknesses in the range of 0.9mm to 1.5mm are in regular production, extending the strip thickness range for hot rolled strip products and allowing substitution for cold rolled strip products. Several commercial and structural grades are in regular production, with strength levels up to ASTM A1011M SS Grade 380.

In contrast to the fine grained austenite produced by the multiple, high reductions, in conventional hot rolled strip processing, the post hot rolling microstructure of current UCS products has a relatively coarse grained austenite produced by the limited hot reduction (<50%) applied to the as-cast microstructure in the CASTRIP process. The subsequent austenite transformation is assisted by the inclusion engineering practices in the CASTRIP process. In these current steels, a uniform dispersion of fine particles in combination with the coarse austenite grain size is used for particle-stimulated nucleation of intragranular acicular ferrite. The fine interlocking morphology of acicular ferrite is beneficial to strength and toughness [1]. For the current plain low carbon UCS steels, the

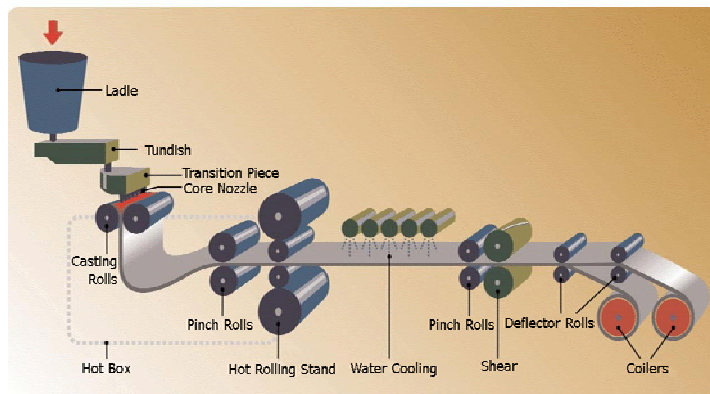


Fig. 1 Main components of the CASTRIP process.

final microstructure has mostly grain boundary ferrite and fine intragranular acicular ferrite. This microstructure is considerably different to conventional hot rolled and cold rolled strip products. Accordingly the effect of the main processing parameters, such as alloy design, hot rolling reduction and cooling profile during the austenite transformation, on the final microstructure had to be determined and related to the mechanical properties of the strip.

More recently the product development focus has been directed at developing higher strength UCS products, with yield strength levels up to 550 MPa. With conventional hot rolled strip products, high strength levels are usually achieved through the use of one or more of the microalloying elements Ti, Nb and V in combination with thermo-mechanical processing to achieve strengthening through ferrite grain refinement and precipitation hardening. Thermo-mechanical processing essentially involves considerable refinement of the initial austenite grain size by deformation in the austenite recrystallisation temperature range, followed by significant reduction in the non-recrystallisation regime, and often coupled with accelerated cooling practices after finish rolling, to achieve the required ferrite grain refinement. In the case of UCS products this conventional strengthening approach is not applicable. Therefore for UCS steels, other strategies were required to be developed to achieve higher strength products. This paper investigates the behaviour of Nb in UCS steels, in a regime of a coarse austenite grain size and low hot rolling reductions, which has previously not been explored.

ULTRA THIN CAST STRIP MANUFACTURE BY THE CASTRIP PROCESS

The CASTRIP twin-roll casting operations utilises two counter rotating rolls to form two individual shells that are formed into a continuous sheet at the roll nip. The main components of the CASTRIP facilities at Nucor Steel Crawfordsville are depicted in Figure 1. The ladle size used is 110 metric tonnes, which feeds a large conventional tundish and then a smaller tundish or transition piece. The transition piece is designed to reduce the ferrostatic head of the liquid steel as well as distribute the metal flow across the barrel length of the casting rolls. The core nozzle sits between the casting rolls, immersed in the metal pool, to deliver liquid metal to the metal pool. The casting speed is typically in the range of 60-100 m/min and the as-cast strip thickness is typically 1.7mm or less. The in-line hot rolling mill is capable of up to 50% hot reduction. The water cooling facility, located immediately after the rolling stand, provides cooling through the austenite to ferrite transformation to achieve the required cooling rate and coiling temperature. More details of the CASTRIP process have been reviewed elsewhere [2,3].

In the CASTRIP process, the steel compositions presently produced are low carbon ($<0.05\%$)-manganese-silicon steels. This alloy design was developed to ensure the deoxidation products of MnO and SiO₂ are liquid during the casting process to avoid clogging and to enhance the heat transfer rate to the casting rolls [4]. The rapid solidification rates with the strip casting process can, with control of certain parameters, provided a fine and uniform distribution of globular inclusions through the strip thickness (Figure 2).

Importantly, the formation of type II MnS stringer inclusions which are often found in Al killed steel strips produced from conventional slab casting processes, was avoided. Together with the low in-line hot rolling reductions, elongated inclusions are avoided in UCS products to the benefit of forming, shearing or punching operations. The Mn-Si deoxidised steel practice additionally provides flexibility for setting appropriate dissolved oxygen levels that are not possible in conventional Al killed steels. In the CASTRIP process, the resultant inclusion/ particle populations are tailored to achieve particle-stimulated intragranular nucleation of acicular ferrite. The size range of the globular inclusions in UCS products typically varies from about 10 μ m down to very fine particles, less than 0.1 μ m. A large proportion of the inclusions are in the 0.5 μ m to 5 μ m size range. The larger 0.5-10 μ m size non-metallic inclusions are pivotal in the development of the final microstructure, since they are the particles that are effective in nucleating acicular ferrite. Some of these inclusions are composed of a complex mixture of phases including MnS, TiO and CuS.

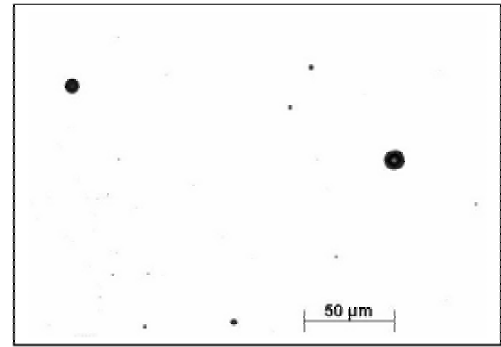


Fig. 2 Typical worst case field showing globular inclusions found in as-cast UCS

PLAIN LOW CARBON STEEL

Microstructure

A key feature of the final microstructure for current plain low carbon UCS steels is the formation of particle-stimulated nucleation of intragranular acicular ferrite. Typical examples of the final microstructure of as-cast strip are shown in Figure 3a,b. Figure 3a shows the microstructure is composed of irregular shaped grain boundary ferrite that formed along the prior austenite grain boundaries, some Widmanstätten ferrite and intragranular acicular ferrite. Figure 3b shows intragranular acicular ferrite nucleated on a typical non-metallic inclusion. This microstructure is beneficial for improving the strength and toughness of steel, particularly in the case of a coarse austenite grain size.

The sequence leading to the formation of the acicular ferrite microstructure in these current UCS steels is shown schematically in Figure 4 [5]. The first transformation product to form during the decomposition of austenite for the low C-Mn-Si alloys is a thin layer of allotriomorphic or grain boundary ferrite, which decorates the austenite boundaries. As the temperature decreases, Widmanstätten side plates can nucleate at the γ - α grain boundaries and grow into the untransformed region. On further cooling, acicular ferrite can nucleate at inclusions. Subsequent nucleation events may stimulate other plates to nucleate sympathetically so that a one to one correlation with the number of nucleation events and inclusions is not expected [6]. As many ferrite plates nucleate at essentially the same time, nearby plates impinge upon each other creating a characteristically fine interlocking plate morphology. Evidence of this mechanism, including the intragranular nucleation of multiple plates of ferrite, is clearly shown in Figures 3a-b.

Four main mechanisms for the nucleation of acicular ferrite at inclusions have been postulated [7,8,9] and may even work in combination. They are briefly summarised below:

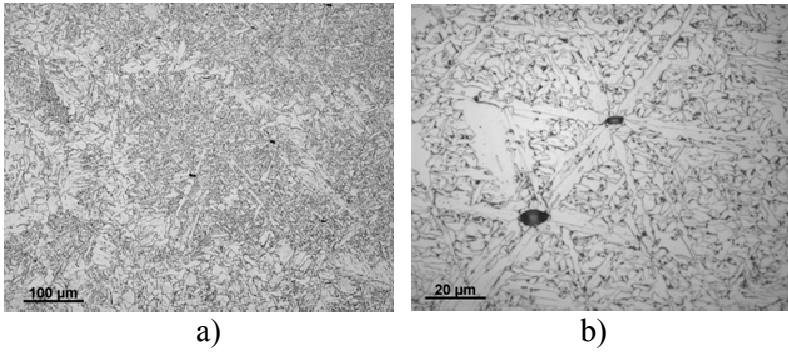


Fig. 3 Micrographs of recent UCS steels, where a) is predominantly acicular ferrite with pro-eutectoid ferrite decorating the prior austenite grain boundaries and b) shows acicular ferrite nucleating at two non-metallic inclusions.

expansion properties of the inclusion and matrix locally raise the strain energy which reduces the activation energy for nucleation.

Inclusion size is critical to the intragranular nucleation of acicular ferrite. Larger particles increase the probability of nucleation of acicular ferrite and the minimum particle size required has been suggested to be 0.4-0.6μm [10,11]. The inclusion size distribution found in the UCS product recently produced by the CASTRIP process fits well into this suggested particle size range. Besides the influence of the inclusion type, number density and population size on the formation of intragranular acicular ferrite, the other main factors are the austenite grain size, steel hardenability and the cooling rate through the transformation from austenite [12].

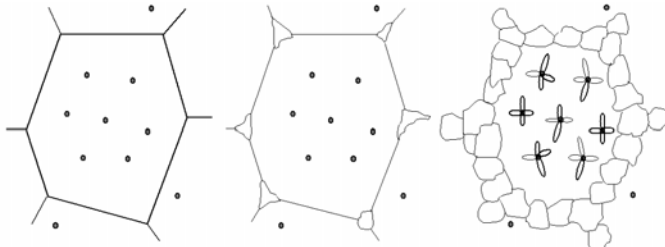


Fig. 4 Schematic of the formation of acicular ferrite microstructures. After Barbaro 2006 [5]

In current UCS steels, the austenite grain size is relatively coarse where individual grain widths and lengths can be greater than 200 and 450μm respectively. Subsurface grains are slightly finer than the grains in the central area of the strip, presumably reflecting the difference in thermal history and the influence of

nucleation rate during initial solidification on the subsurface grain size [3]. While coarse austenite grain size is a prerequisite for the formation of acicular microstructures, the final microstructure depends on the alloy design and processing conditions, namely, the degree of in-line hot reduction and the cooling profile on the run-out table, which are discussed below.

Effect of Hot Reduction

Figure 5 shows an example of the effect of hot rolling on the final austenite grain size measured through the thickness of a recently produced plain low C UCS strip. Significant recrystallisation occurred for reductions of 22% and had extended through the full strip thickness at reductions of 29%. Recrystallisation of the subsurface grains occurs before the central region because of the finer as-cast austenite grains in the subsurface area and the through-thickness strain gradient induced by friction between the strip surface and the work rolls. The finer recrystallised austenite grains reduced the hardenability and consequently the proportion of acicular ferrite formed. For this reason, the level of hot reduction applied for manufacture of high strength grades can be limited. The effect of hot rolling reduction on austenite grain size refinement and in turn the final

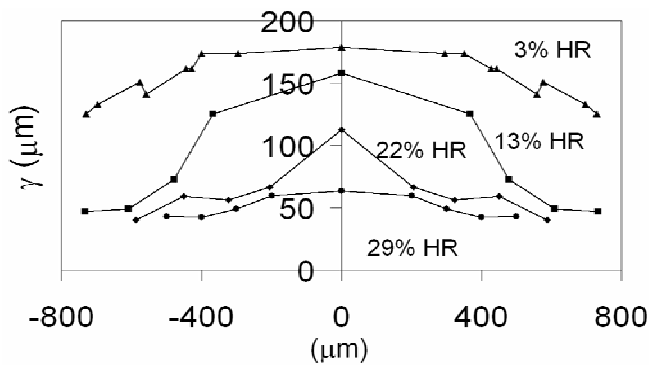


Fig. 5 Effect of hot rolling reduction on austenite grain size measured through the thickness of a UCS strip.

microstructure for a narrow coiling temperature range of about 600-620°C is illustrated in Figure 6. The proportion of acicular ferrite decreased with increasing hot reduction (Figure 6a) and was replaced by an increased proportion of polygonal or quasi polygonal ferrite. The ferrite grain size was also refined with increased hot rolling, as shown in Figure 6b. Decreasing the carbon content (lower carbon equivalent) also resulted in a reduction in the amount of acicular ferrite (Figure 6a), consistent with a lower steel hardenability.

The engineering stress-strain curve and mechanical properties of the plain low UCS steel also reflected changes in the microstructure, as shown in Figure 7a. Figure 7b illustrates the changes in the tensile properties with in-line hot rolling reduction, for a constant coiling temperature. Lower amounts of acicular ferrite results in reduced strength and higher total elongation when hot reduction levels exceed about 15%. At higher reduction levels, the increased refinement of ferrite offset the reduction in acicular ferrite content, such that strength levels did not change or even increased slightly. The final tensile properties are also influenced by the coiling temperature, along with the steel composition. The effects of hot rolling reduction are diminished at low cooling rates/high coiling temperatures in comparison to high cooling rates/low coiling temperatures.

Effect of Coiling Temperature

The effect of the coiling temperature on the strength of two recently made plain C UCS steels, at two levels of Mn (0.60% and 0.80%), is shown in Figure 8a. Figures 8b-d shows the change in microstructure with cooling stop temperature. For these plain C steels, the yield strength increased with decreasing cooling stop temperature for temperatures down to about 550°C. Below this temperature the strength increased only slightly with further reductions in cooling stop temperature. Lower cooling stop temperatures increased the yield strength due to the replacement of grain boundary ferrite with acicular ferrite. Figures 8b-d shows the change in microstructure with changes in the ROT cooling conditions. Air cooling produced predominately a polygonal/non polygonal ferrite microstructure (Fig 8b), a high cooling stop temperature produced some acicular ferrite (Fig 8c), and a low cooling stop temperature produced a predominately acicular ferrite structure (Fig 8d). The higher Mn Steel (0.80%Mn, Fig 8a) provided an increase in strength at lower coiling

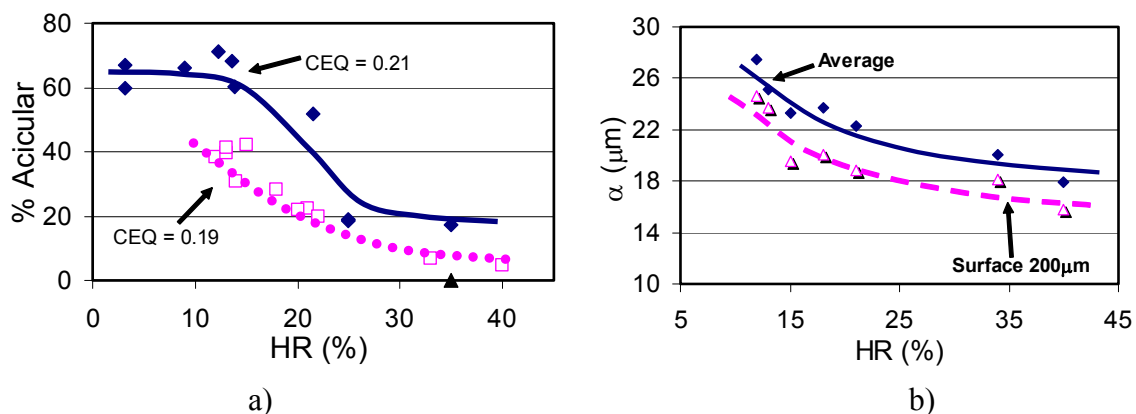


Fig. 6a) Effect of hot rolling on the evolution of acicular ferrite and b) grain boundary ferrite grain size of plain low C UCS strip, produced by the CASTRIP process.

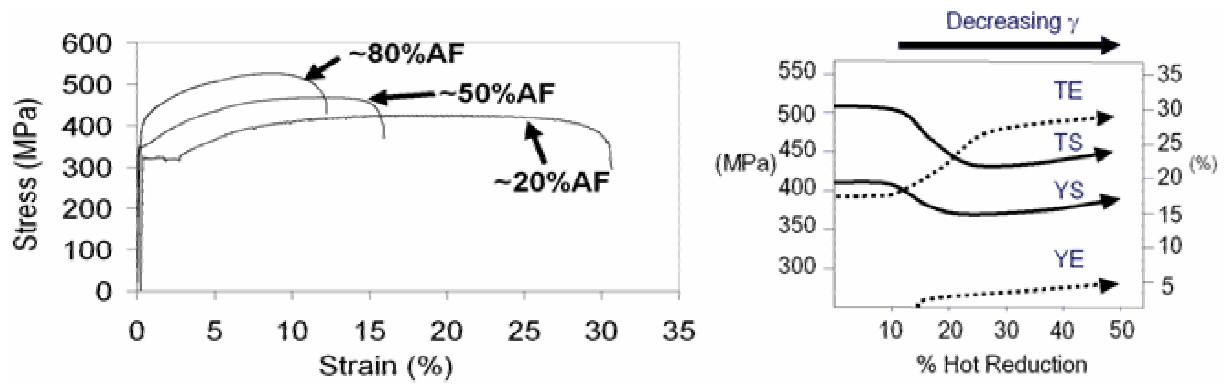


Fig. 7 a) Engineering stress-strain curves for as-cast (80% AF), 14% (50% AF) and 25% (20% AF) hot reduction. b) Schematic representation of the mechanical properties of UCS material as a function of hot rolling reduction at constant coiling temperature. Total Elongation (TE), Tensile Stress (TS), Yield Stress (YS) and Yield Elongation (YE).

temperatures due to an increased proportion of acicular ferrite, reflecting the steel's higher hardenability. As the cooling rate was not sufficient to completely suppress the formation of grain boundary ferrite in the plain, low C steels, the strength approached a plateau for coiling temperatures below 550°C. Overall, the combination of coiling temperature control and modest alloy adjustments enabled a range of structural steels to be produced from these plain, low C steels.

Mechanical properties

The main commercial and structural strip products currently produced at Nucor Steel's Crawfordsville CASTRIP facility from plain low C steels are ASTM A1011M Grade CS and SS grades 275, 310, 340 and 380 MPa. UCS steels can meet the requirements of these grades quite

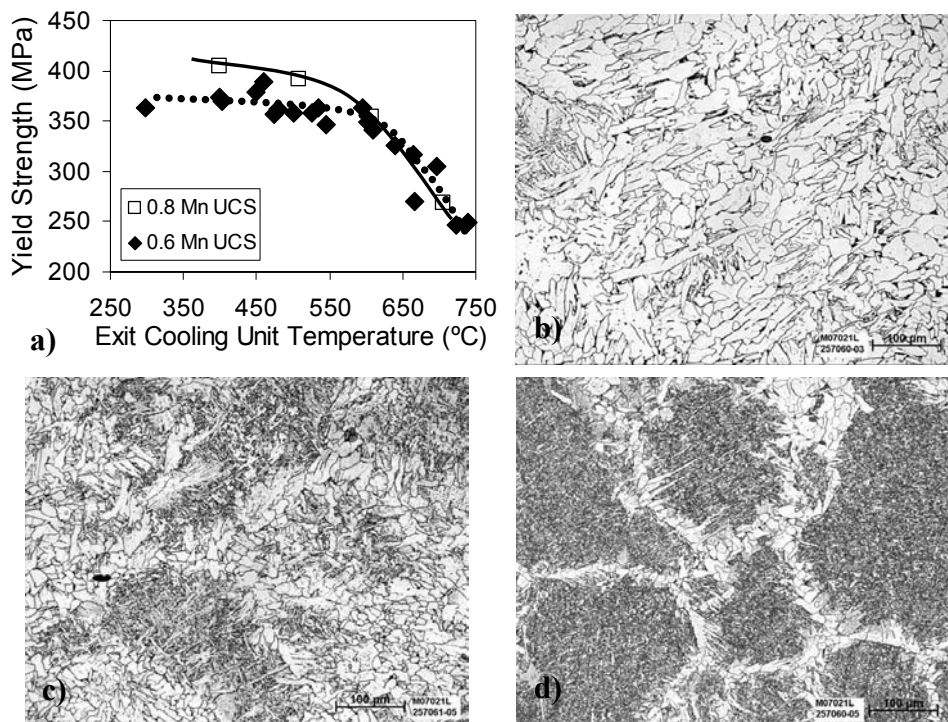


Fig. 8 Effect of run-out-table cooling conditions on the yield strength and microstructure of UCS; a) effect of cooling stop temperature on yield strength for 0.60 and 0.80% Mn levels, and effects on microstructure for b) air cooled, c) cooling stop temperature 645°C; d) cooling stop temperature 505°C.

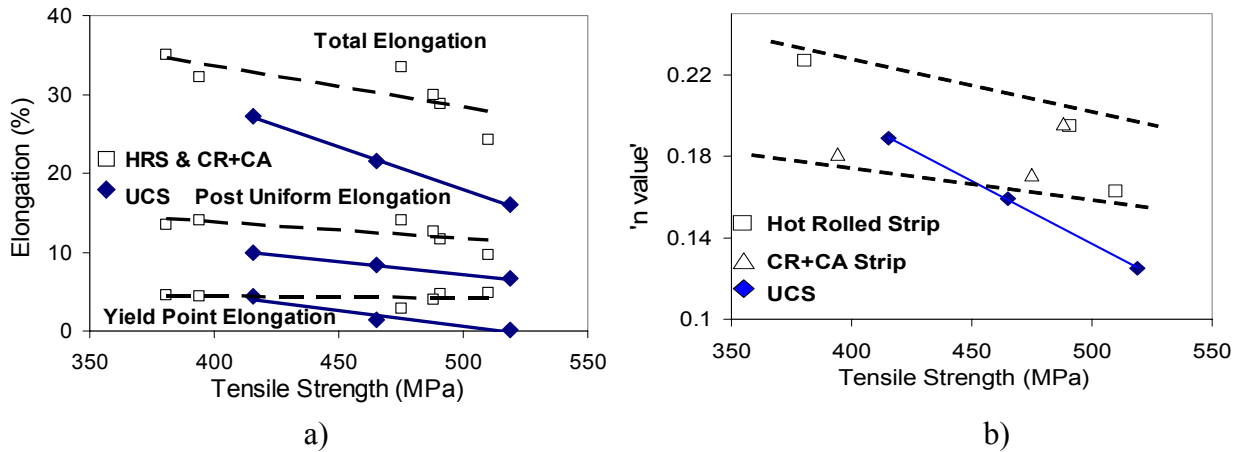


Fig. 9 a) Comparison of elongation components from the uniaxial tensile test for UCS, HRS and CR and CA strip products, b) comparison of the strain hardening capabilities for UCS, HRS and CR and CA products. Gauge length 80mm.

comfortably through adjustments to the coiling temperature and manganese content. The typical chemical composition and tensile properties for each structural product are given in Table 1. The tensile property requirements for these grades have been comfortably achieved. A characteristic of the tensile properties is the relatively low yield/ tensile strength ratio, which affords the steel considerable strain hardening capacity and aids roll forming. The total elongation (TE) values can be somewhat lower than comparable conventional hot and cold strip grades, as shown in Figure 9a. This behaviour can be attributed to the microstructure being mainly a mixture of grain boundary ferrite and acicular ferrite. The lower TE values in UCS steels are mainly a resultant of the lower post uniform elongation and yield point elongation components of the TE, Figure 9a, the latter being minimal for the higher strength grades due to the high proportion of acicular ferrite [13].

Table 1: Typical chemical compositions and tensile properties for selected structural UCS products.

Product	C (wt%)	Si (wt%)	Mn (wt%)	Al (wt%)	N (ppm)	t (mm)	YS (MPa)	TS (MPa)	TE (%)
275 UCS	0.03 – 0.05	0.10-0.30	0.6 – 0.9	<0.003	35-90	1.0 – 1.7	325	430	28
340 UCS	0.03 – 0.05	0.10-0.30	0.6 – 0.9	<0.003	35-90	1.2 – 1.7	375	475	21
380 UCS	0.03 – 0.05	0.10-0.30	0.7 – 1.0	<0.003	35-90	1.4 – 1.7	430	525	18

The strain hardening exponent (n-value) is one of the more significant indicators of formability from the uniaxial tensile test. The n-values for the UCS structural products are presented in Figure 9b in comparison to comparable hot and cold rolled structural grades. The n-values for the UCS products 275 and 340 are similar to comparable cold rolled and continuously annealed steels, while the UCS 380 still exhibited an n-value of about 0.12. Stretch-flangeability is an additional indicator of formability, and is of considerable importance to component manufacturing. The hole-expansion test is commonly used to assess the stretch-flangeability of strip products. Figure 10 shows the % hole-expansion value (λ) for UCS SS Grades 275 and 380 as a function of the tensile strength (Fig.10a) and total elongation (Fig.10b) related to comparable conventional light gauge hot rolled and cold rolled continuously annealed products. It can be seen that for the comparable conventional hot rolled and cold rolled grades λ decreased with increasing tensile strength and decreasing total elongation, reflecting the higher carbon content and accordingly higher pearlite content, used for the higher strength grades. In contrast, the UCS products maintained a high λ at higher strength levels and lower total elongations. Moreover, the UCS products exhibited similar results to the low strength hot rolled grade with higher total elongations. The superior performance of the UCS

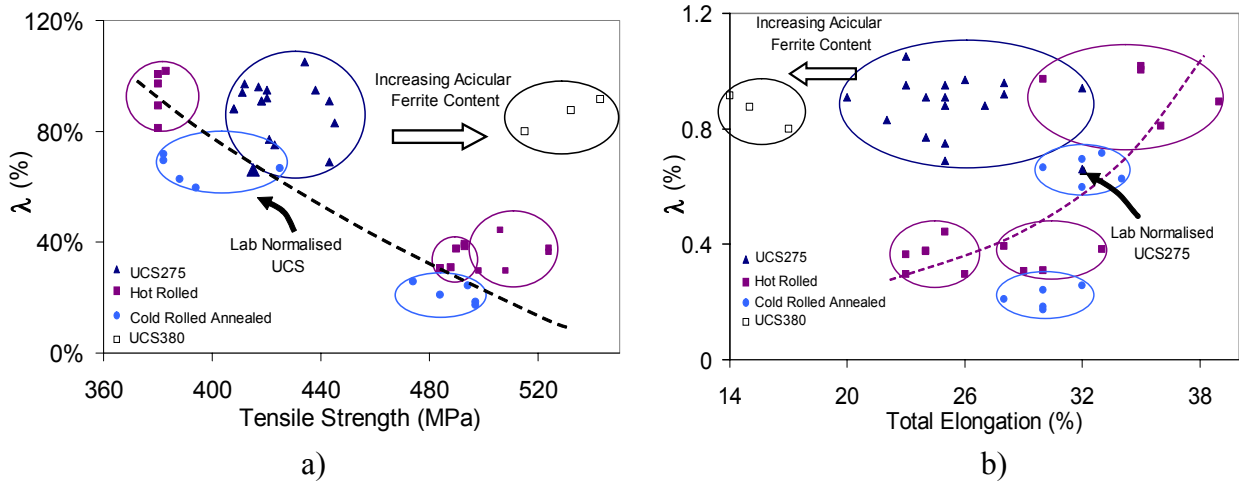


Fig. 10 Hole expansion results for UCS steels 275 and 380 related to comparable structural quality hot rolled and cold rolled strip a) λ as a function of TS b) λ as a function of TE.

products is believed attributable to the acicular ferrite microstructure [13], with small ferrite plates and a fine distribution of small carbides, which provides a high degree of microstructural uniformity that assists micro-plasticity. The absence of elongated MnS inclusions and alumina stringers also enhances λ values [14].

Steel drawability is usually characterised by the average normal anisotropy, r_m and the planar anisotropy, Δr . Table 2 summarises the r_m and Δr values of recently produced UCS products and comparable hot rolled and cold rolled, continuously annealed structural quality products. The UCS products, produced with typical levels of hot reduction (up to 30%) are almost isotropic in behaviour, with r_m values of approximately 1.0 and with low planar anisotropy (Δr) of 0.04. This result is superior to comparable conventional structural quality products, and a direct consequence of less pronounced rolling texture development associated with the low rolling reductions in UCS products. Whilst r_m values for UCS are comparable to those typical of cold-rolled continuously annealed strip, the very low Δr provides for a much reduced earing tendency.

Table 2: Typical r_m and Δr values for UCS products compared with similar thickness and strength hot and cold rolled strip products.

Material	r_m	Δr
UCS (grades 275 to 380)	1.03	0.04
200 HR	0.96	0.10
300 HR	0.93	0.02
300 CR	1.03	0.41

HIGHER STRENGTH NIOBIUM MICROALLOYED STEELS.

Higher strength UCS products have recently been developed with yield strength levels up to 550 MPa by microalloying additions of Nb. The strengthening potential of the current range of plain low carbon steels was restricted to Grade SS380. Moreover, with the current plain carbon steels, the reduction in hardenability due to austenite grain refinement from hot rolling limited the degree of hot reduction, and hence the thickness range for Grade SS380 [15]. Nb microalloyed UCS steels were found to extend the strength and thickness range potential for UCS products. UCS products with Nb additions were found to suppress austenite recrystallisation and enhance hardenability. The inclusion engineering practices, as discussed for the base UCS steel, were still appropriate for providing suitable inclusions to nucleate intragranular acicular ferrite in the Nb microalloyed UCS steels.

A range of Nb microalloyed steels were recently successfully cast in thin strip by the CASTRIP process with the Nb levels systematically varied from 0.014% to 0.084%. The compositions of the trial heats are given in Table 3. The final strip thicknesses produced were in the range of about 1.0mm to 1.5mm, with the in-line hot rolling reductions up to about 40%. Each trial heat was produced in a sequence with non-microalloyed UCS heats. This generated a compositional transition coil between the base composition and the Nb bearing trial heat in each case due to mixing of chemical compositions in the tundish. The casting and processing conditions were constant through the transitions, so that the effect of increased Nb, particularly at low levels of <0.015%, could be assessed progressively through the transition coils.

Table 3: Compositions of the Nb microalloyed trial UCS products, wt%.

Steel	C	Mn	Si	Nb	N
A	0.032	0.72	0.18	0.014	0.0078
B	0.029	0.73	0.18	0.024	0.0063
C	0.038	0.87	0.24	0.026	0.0076
D	0.032	0.85	0.21	0.041	0.0065
E	0.031	0.74	0.16	0.059	0.0085
F	0.030	0.86	0.26	0.065	0.0072
G	0.028	0.82	0.19	0.084	0.0085

Tensile Properties

The average yield and tensile strength results for each trial Nb UCS heat are presented in Figure 11a. The strength level initially increased sharply for low levels of Nb and thereafter incrementally for Nb levels over about 0.02%. The yield strengths determined from a ‘compositional transition’ coil associated with Steel G are also included in Fig 11a. These results are in close agreement with the strength levels of the Nb bearing UCS heats during the trials. Overall, the results show that a 415 MPa UCS product can be achieved using a small addition of Nb and a 450 MPa UCS product could be achieved with higher Nb levels. Thus, the addition of Nb to UCS steels substantially expanded the range of tensile properties achievable from a low C, lean carbon equivalent steel. The total elongation results are presented in Figure 11b. It can be seen that the ductility progressively decreased as the yield strength increased, however the total elongations were still well in excess of the requirements for ASTM A1011 Grade SS410 (8%). Importantly the total elongations were greater than 10%, which is a requirement for sheet steels for cold-formed framing members, ASTM A1003 [16], for application in residential and commercial construction. Metallographic examination revealed the Nb UCS product had achieved the observed tensile properties with considerable microstructural hardening. In particular, a predominantly bainite and acicular ferrite microstructure was observed which was devoid of grain boundary ferrite. The refinement of the microstructure increased with increasing amounts of Nb. The initial steep increase in strength at low Nb levels corresponded to the initial suppression of the formation of grain boundary ferrite, which is formed in the plain low C UCS steel. Transmission electron microscopy (TEM) examination of the microalloyed UCS steels C and F (Table 3) did not reveal any evidence of Nb precipitation. This indicates that strengthening in the Nb UCS product was primarily due to microstructural hardening.

Effect of Hot Rolling and Coiling Temperature

The effect of in-line hot rolling reduction on the yield strength for the Nb UCS product is shown in Figure 12a compared to the plain C UCS steel. Whilst hot reduction level markedly influences the strength of the higher strength plain C UCS steel, the Nb UCS products were little affected at least for hot reduction levels of up to 50%. The suppression of austenite recrystallisation with Nb additions removed the limitation of relatively high hot reductions that restricted the use of plain low

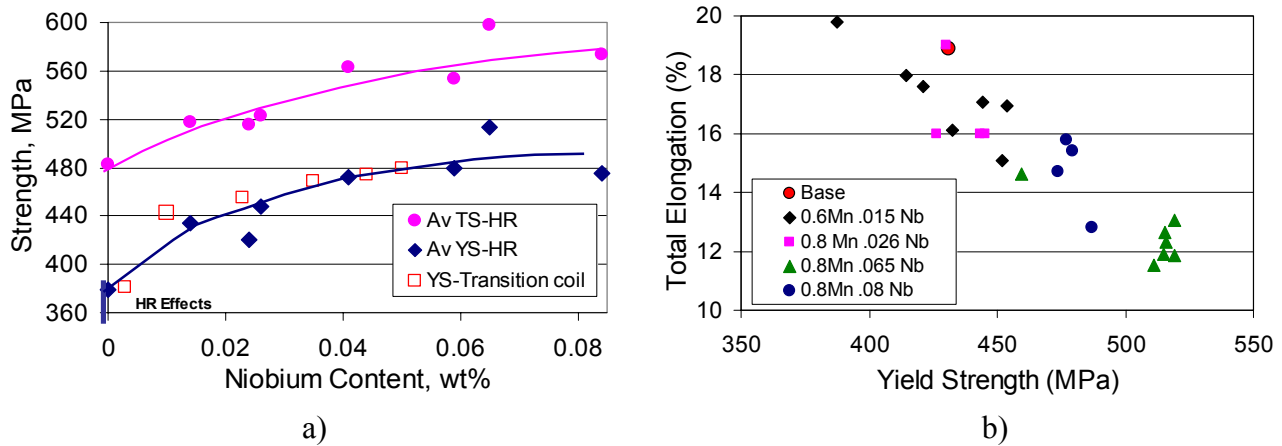


Fig. 11a) The effect of Nb content on the average yield strength and tensile strength of hot-rolled Nb UCS steels. 11b) The change in total elongation with yield strength for the Nb microalloyed UCS steels.

C-Mn-Si steels for high strength UCS products. Thus, for a particular strength grade, a Nb microalloyed UCS steel can be applied over the full potential thickness range for UCS products.

As noted earlier, in plain C UCS steel after sufficient in-line hot reduction at the rolling temperatures used in UCS products (i.e. about 950°C), austenite recrystallisation occurred. By contrast, Nb UCS steels prevented austenite recrystallisation under these conditions. Figure 13 shows the relatively undeformed coarse equiaxed austenite grains observed in Nb UCS Steel F (Table 3) after 15 % hot reduction (Fig.13a) compared to a higher level of 35% reduction, which showed a more deformed or pancaked austenite structure, (Fig. 13b). The retention of the coarse unrecrystallised austenite grain structure, even after the heavier rolling pass reduction level, preserved high hardenability, which assisted with producing lower temperature transformation products such as bainite and acicular ferrite in the final microstructure; resulting in strength levels largely independent of the degree of hot rolling reduction.

The effect of the coiling temperature on the yield strength for the Nb microalloyed UCS steels is compared to the response of the plain low C UCS steel in Figure 12b. The Nb UCS steels were much more resistant to softening at higher coiling temperatures. Again this reflects the increased hardenability of Nb UCS products, which allows a wider operational range of coiling temperatures to be specified to achieve the required strength levels. The effect of coiling temperature on the final microstructure is illustrated using the 0.024% Nb UCS product, where a series of micrographs are

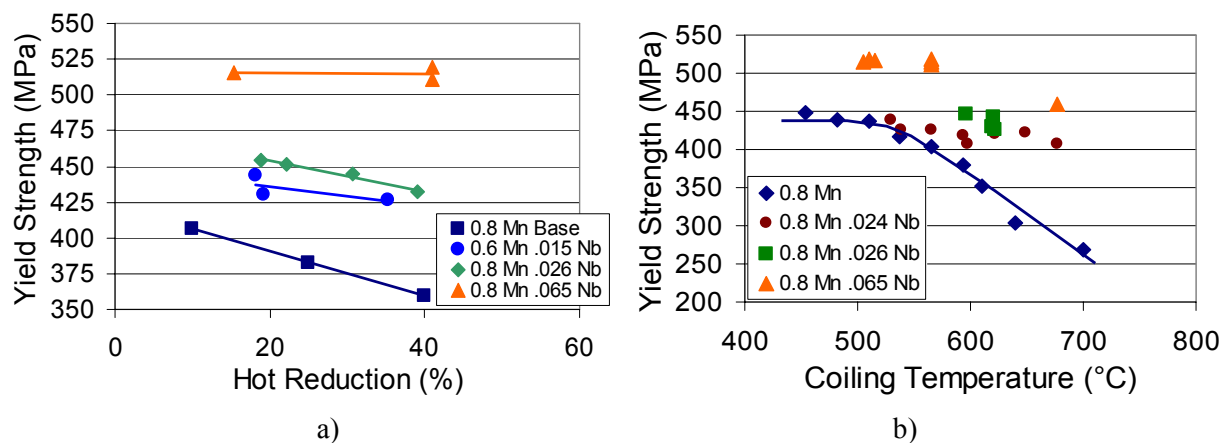


Fig. 12a) Effect of hot reduction on yield strength and b) Effect of coiling temperature on yield strength of the C-Mn-Si base UCS steel and various Nb microalloyed UCS steels.

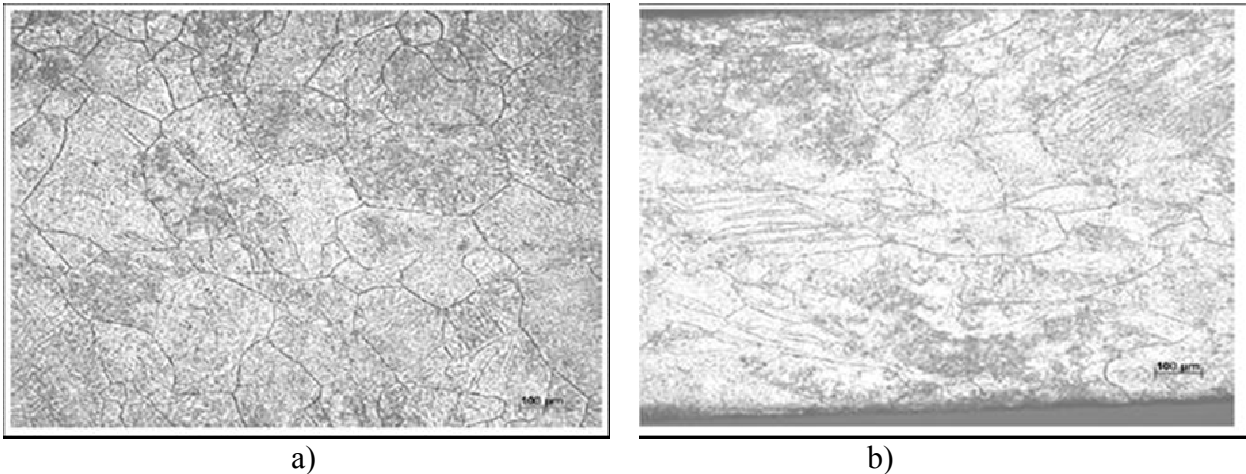


Fig. 13 Unrecrystallised austenite grains in Nb UCS Steel F after a) 15% hot reduction and, b) 35% hot reduction.

shown in Figures 14a-d for coiling temperatures of 490°C, 535°C, 570°C and 650°C, respectively. With increasing coiling temperature, a progressively coarser bainitic microstructure was achieved in preference to the formation of acicular ferrite. At the highest coiling temperature (650°C, Figure 14d), a significantly coarser microstructure was observed. However, this change in microstructure in the UCS Nb products was not reflected in the strength levels, except for the coarse bainitic microstructure at the highest coiling temperature. This possibly accounts for the slightly lower strength at this coiling temperature for both the 0.024% and 0.065% Nb UCS steels (Figure 12b). A key feature of the microstructures, even at the highest coiling temperature shown, is that a highly interlocking plate or lath structure is produced, which ensures a good combination of strength, formability and toughness.

Effect of Niobium Content

The effect of the Nb level on the strength and final microstructure in the UCS products was further evaluated by progressively examining ‘compositional transition’ coils, described earlier. The increase in yield strength with increasing Nb content is shown in Figure 15a. For the ‘compositional transition’ coil associated with the 0.084% Nb UCS steel (Steel G), there was a substantial initial yield strength increase of about 60 MPa to 440 MPa with 0.010% Nb and thereafter the strength level continued to progressively increase, but at a lower rate, to about 480 MPa at 0.05% Nb. This strengthening response with increasing Nb level in UCS products is consistent with the results for the trial heats, (Figure 11a) and shows the repeatability of the strengthening behaviour of Nb UCS steels. The effect of the Nb content on the final microstructure is shown quantitatively in Figure 15b, in terms of the proportion of acicular ferrite and bainite phases measured from the coil microstructures.

For the plain C UCS steel (without Nb) the microstructure consisted of grain boundary ferrite and acicular ferrite as previously discussed. A significant reduction in grain boundary ferrite formation and a refinement of the microstructure occurred even with 0.010% Nb in the UCS product, accounting for the substantial initial strength increase recorded. The vast majority of the grain boundary ferrite had been replaced with bainite at the 0.023% Nb level in the UCS product. With continuing increases in Nb the proportion of bainitic phases increased and the volume fraction of acicular ferrite diminished. This progressive change in the proportion of the bainitic and acicular ferrite phases may relate to the steady strength increment recorded in the Nb UCS steel, with increasing Nb content, after the grain boundary ferrite had been replaced with bainite. The role of Nb on the hardenability in UCS steels was further shown by the ‘compositional transition’ coils generated for two low Nb steels (containing 0.015% Nb), Figure 15. The enhanced hardenability in

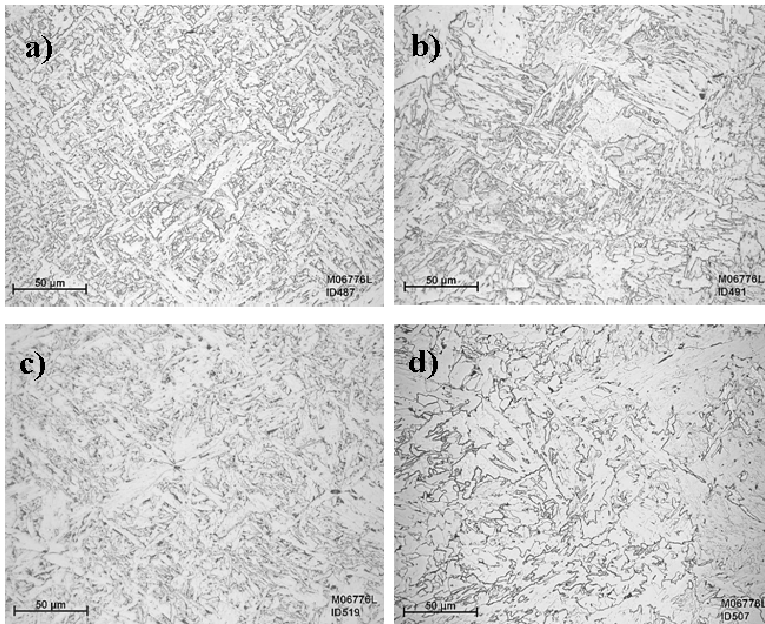


Fig. 14 Microstructures for 0.024%Nb UCS steel at different coiling temperatures, a) 490°C, b) 535°C, c) 570°C and d) 650°C.

size (via austenite conditioning) and precipitation hardening of ferrite. By contrast, with UCS products, Nb additions are fully retained in solid solution due to the thermal path and limited degree of hot rolling, employed in the process. Together with the coarse (un-recrystallised) austenite grain size and specially engineered inclusion particles unique to UCS, the microstructural hardening capability of Nb can be fully exploited in UCS products.

Age Hardening Heat Treatment

As noted earlier, TEM examination did not reveal any Nb precipitation in the hot rolled condition. This suggests that Nb was held in solid solution and potentially available for age hardening in the Nb UCS steels. To further investigate the state of Nb, laboratory age hardening heat treatments were undertaken on a range of the Nb UCS trial steels. Short time heat treatments were carried out using an electric resistance heated continuous annealing simulator, utilising a time-temperature cycle to simulate the continuous annealing section of a galvanising line for a range of peak temperatures and times. As an example, the response of the 0.084% Nb UCS steel to heat treatment is given in Figure 16a. The yield strength follows a typical age hardening response, with strengthening beginning at

the UCS steel with low Nb additions was shown even with high hot rolling reductions of about 40% and high coiling temperatures of about 650°C. The higher resultant strengths at low Nb levels (Figure 15a), could be explained by higher proportions of bainite and acicular ferrite (Figure 15b). The potent effects of Nb on the hardenability of UCS steels and consequently enhanced yield strengths are clearly evident from the transition coils data.

In most conventional Nb microalloyed hot rolled products the Nb is generally not retained in solid solution and the main strengthening mechanisms involve a combination of fine ferrite grain

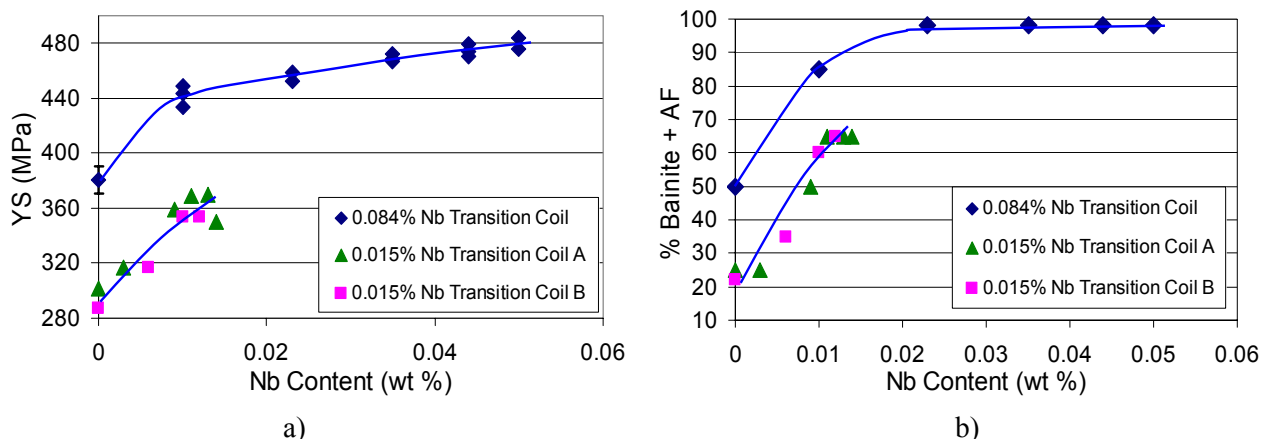


Fig. 15 Influence of Nb content on a) the yield strength and b) the final microstructure.

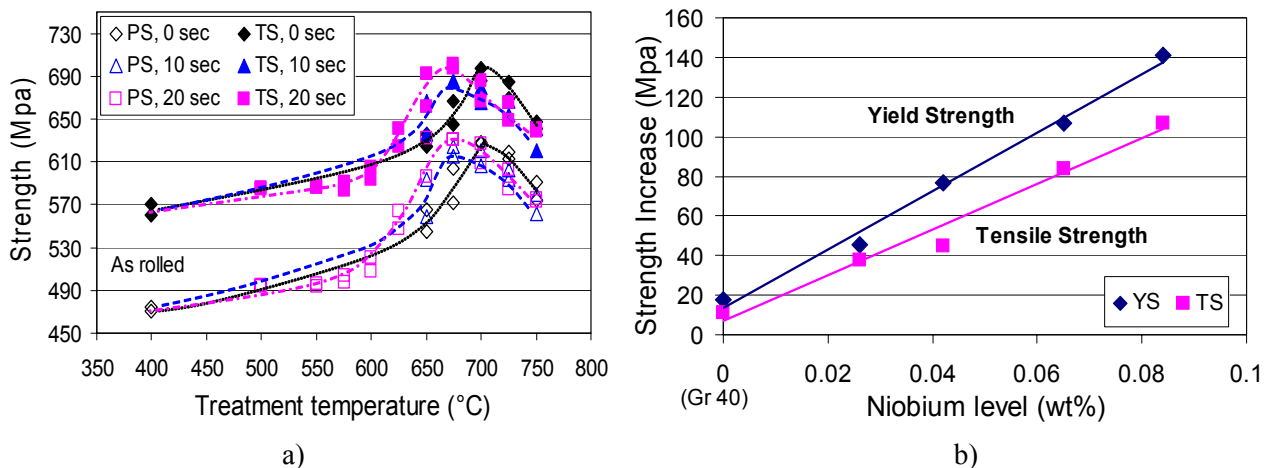


Fig. 16 Laboratory age hardening of Nb UCS steels. a) Effect of temperature peak and holding time on strengthening response for the 0.084% Nb UCS steel. b) Strength increase between the hot rolled and maximum age hardened strengths as a function of Nb level.

about 625°C, maximum strengthening occurring in the temperature range of 675 to 725°C and over ageing beginning to occur at 750°C. The maximum strength increment was about 150 MPa, producing yield strengths of over 600 MPa. The temperature for peak strengthening was slightly higher for the shortest hold time, though the results for 10 and 20 seconds were similar, indicating the strengthening response was not overly sensitive to time at temperature. TEM examinations were carried out on samples that had been heat treated in the over ageing temperature regime (750°C) where particle coarsening would be expected to aid identification. Very fine precipitates were found in the size range of 4-15nm and were identified as being Nb rich, indicating the observed strengthening increment was due to age hardening phenomena. Figure 16b summarises the age hardening response for a range of the trial Nb UCS steels, where the maximum strength increment is presented as a function of the Nb content of the steel. The results show a progressive increase in age hardening with increasing Nb level. The heat treatment cycle also produced a small increase of about 20 MPa in the yield strength of the plain low C UCS steel. This suggests that the strengthening increment attributable to age hardening in Nb UCS may be about 20 MPa less than the total strength increment achieved from the heat treatment cycle. Carbon retained in solution due to air cooling from the peak temperature may account for this strength increment noted with the plain C UCS steel.

The age hardening response of Nb UCS steels observed in the short time heat treatments indicated the potential for age hardening these steels using a continuous annealing line or the annealing section of

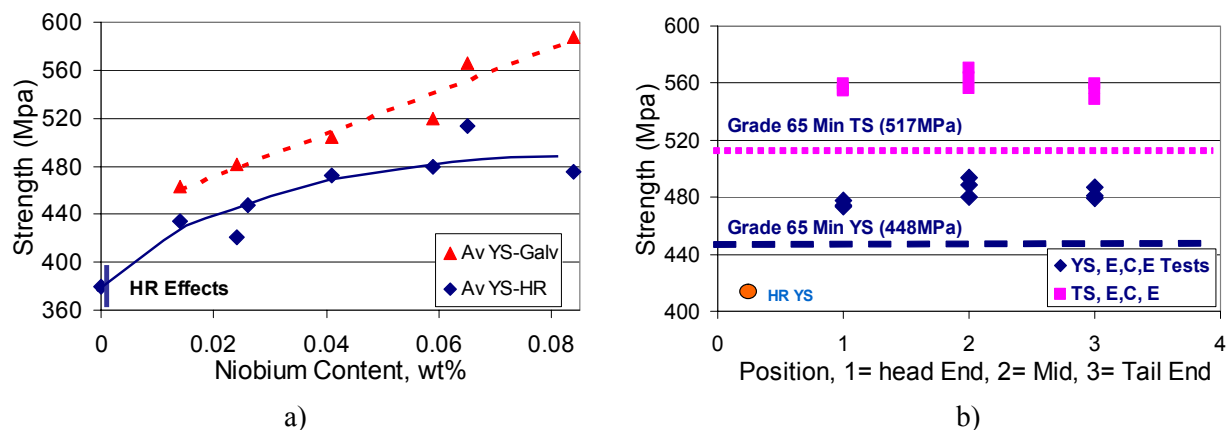


Fig. 17 Age hardening response of Nb UCS steels observed after processing through a continuous hot dip galvanising line in terms of a), effect on yield strength levels as a function of Nb content and, b) through coil yield and tensile strength variation for a coil of UCS Steel B (0.024%Nb).

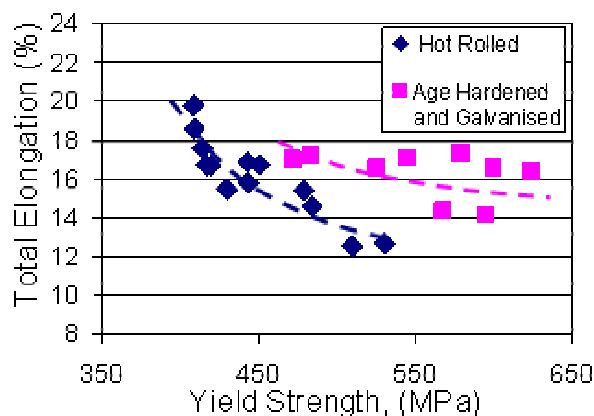


Fig. 18 Comparison of total elongations results between hot rolled and age hardened and galvanised Nb microalloyed UCS steels

a hot dip continuous galvanising line. The processing temperature range seemed adequate and the strength increment required could be controlled by the Nb content. Subsequently plant scale trials were conducted on the hot dip galvanising line at Nucor's Crawfordsville plant to age harden the Nb UCS steels. The results from the full scale production trials are summarised in Figure 17a for a range of the Nb UCS steels and the results for an individual coil (Steel B) are presented in figure 17b. Significant and consistent strengthening was observed using the short heat treatment cycle on the hot dip continuous galvanising line. The final strength

levels recorded were similar to that produced with the laboratory heat treatments of the respective Nb UCS steels. Final strength levels of over 450 MPa were recorded with the 0.024% Nb UCS steel (Steel B) and over 550 MPa with the higher Nb UCS steels (Steels G & H). This outcome indicates the potential to further expand the range of UCS products to higher strengths and significantly increase the strength-thickness combinations possible for hot rolled structural strip grades.

With regard to ductility for the age hardened and galvanised Nb UCS product, the total elongation results are presented in Figure 18, compared to results for the as-hot rolled Nb UCS steels. The results highlight that instead of an expected reduction of total elongation with increasing strength from age hardening, the total elongations were actually either similar or higher in the age hardened and galvanised condition compared to the as-hot rolled UCS product. The microstructural changes that have produced this outcome are still under investigation.

Formability

The stretch-flangeability of the Nb microalloyed UCS steels in the hot rolled and in the age hardened and galvanised conditions were tested using the commonly applied hole-expansion test. The results are presented in Figure 18 in comparison to the results for the plain low C UCS steels and some conventional hot rolled and cold rolled, continuously annealed structural quality grades of similar thickness (previously given in Figure 10). Superior results to conventional steels were obtained for the plain C UCS steels at comparable tensile strengths. The Nb UCS steels also showed superior hole expansion values compared to conventional structural quality steels. In the hot rolled condition the results for Nb UCS steels were similar to the lower strength plain C UCS steels, while in the age hardened steels the results were only slightly lower than the hot rolled condition despite tensile strengths of up to 650 MPa. The excellent performance can be attributed to the refined bainite and acicular ferrite microstructure with a fine distribution of small carbides in the Nb UCS steels, which provides a high degree of microstructural uniformity that assists microplasticity. It is also likely that the small globular nature of the non metallic inclusions in these Nb UCS steels assisted in the excellent hole expansion behaviour. This property attribute is important to high strength steels for structural and component applications where forming of sheared edges is often required.

In the Nb UCS steels, the normal (r_m value) and planar anisotropy (Δr) were measured using the standard tensile test. The r_m results were in the range of 0.95 to 1.03 for both the hot rolled and age hardened and galvanised conditions, with the results at the lower end of the range from material produced with relatively high in-line hot reductions (~40%). The Δr values were about 0.05 for both conditions. The r_m and Δr results are very similar to the plain low C UCS steel values (Table 3),

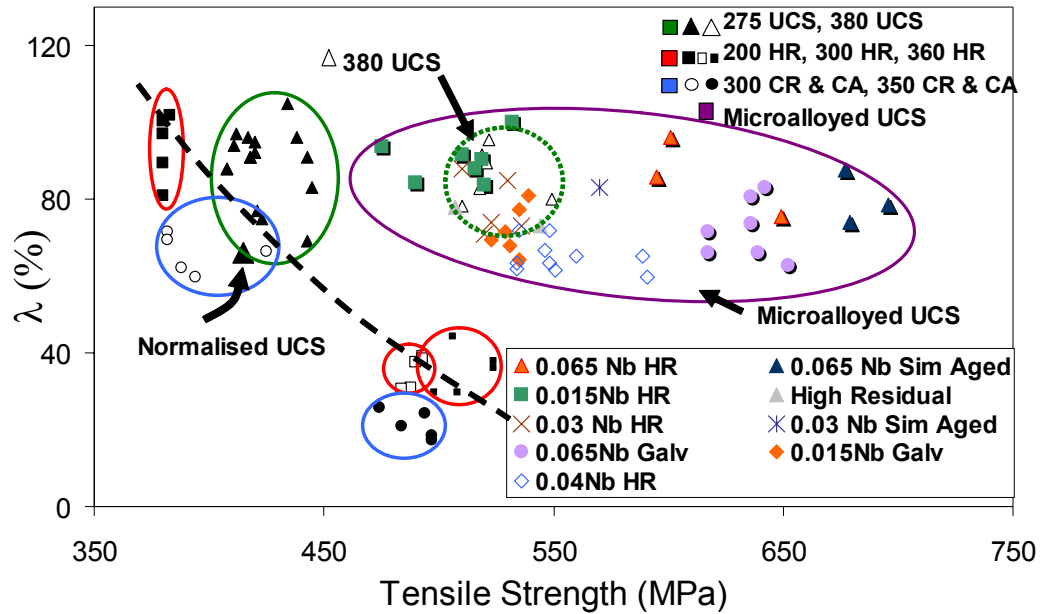


Fig. 19 Stretch-flangeability as measured by the hole expansion test as a function of tensile strength for the plain low C base grade and Nb microalloyed UCS products, compared to conventional hot rolled and cold rolled, continuously annealed structural quality strip grades.

again highlighting the isotropic behaviour of UCS products. These results are superior to conventionally produced Nb microalloyed high strength hot rolled strip, where heavy austenite conditioning for ferrite grain refinement normally lowers r_m values and increases Δr due to the development of rolling deformation textures.

The drawability was further assessed by determining the limiting drawing ratio (LDR) using Swift cups, with a cup diameter of 50mm. The LDR is the ratio of the maximum blank diameter to the cup diameter. Previously a UCS ASTM 1011M SS Grade 275 product was found to have a LDR of 2.3, which was consistent with the r_m of 1.03. The LDR's for the trial Nb UCS Steel F, at 1.4mm thick, in the hot rolled (YS ~ 500 MPa) and the age hardened and galvanised condition (YS ~ 600 MPa) were determined to be 2.1 and 2.2 respectively. This compares with a result of 2.1 for a conventional 300 MPa structural hot rolled strip product. Again the good LDR results for the high strength UCS products probably reflect the r_m values of 0.96 and 1.02 respectively. The cups also exhibited minimal earring, consistent with the isotropic behaviour (low Δr) of UCS products.

SUMMARY

The CASTRIP facility at Nucor's Crawfordsville, Indiana plant currently produces a range of commercial and structural quality UCS products from plain low carbon steels. A number of commercial and structural grades are now in regular production, covering grades up to ASTM A1011M SS Grade 380 MPa and strip thicknesses in the range of 0.9mm to 1.5mm. The product design of UCS steels involves design of the alloy composition, in-line hot rolling reduction and ROT cooling profile, to control the hardenability and transformation of a relatively coarse austenite grain size. The inclusion engineering developed to facilitate casting by the CASTRIP process produces inclusions that assisted with the control of austenite transformation by promoting particle-stimulated nucleation of intragranular acicular ferrite. This provides a final microstructure in the UCS product comprising mostly grain boundary ferrite and fine intragranular acicular ferrite. The relative proportion of each phase largely controls the final strength properties of the UCS product.

The refined microstructure provides satisfactory formability for a range of applications and offers a high level of stretch-flangeability.

A range of Nb microalloyed UCS steels have recently been successfully cast by the CASTRIP process. The niobium microalloying retarded austenite grain refinement from in-line hot rolling and suppressed proeutectoid ferrite formation, which resulted in microstructural hardening and higher strength levels to be achieved than from a plain low C UCS steel. Using the annealing furnaces of a conventional hot dip galvanising line, the Nb UCS steels could be age hardened to produce significant increases in both strength and ductility. The age hardening behaviour can be attributed to the highly effective retention of Nb in solid solution in the UCS steel. Consequently, yield strength levels of over 550 MPa in hot dip galvanised low C, low carbon equivalent, Nb microalloyed UCS steels can be achieved, in combination with good ductility, thereby expanding the potential application of these hot rolled strip products for structural applications.

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